

“Trait” and “state” aspects of fixation disparity during reading

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In our study, 14 subjects read 60 sentences from the Potsdam Sentence Corpus twice (viewing distance: 60 cm), while eye movements were measured with the EyeLink II. We analyzed fixation disparities for complete sentence replications (N=388). After subtracting the average fixation disparity of each sentence from each observation (which gave the “state” fixation disparity), 99% of all remaining fixation disparities were aligned, i.e. smaller than one character width (20 min arc) – depending mostly on incoming saccade amplitude and fixation position. Additionally, we measured the heterophoria for each subject during calibration and found a qualitative relationship between average, individual measures of fixation disparity (“trait” fixation disparity) and heterophoria, after dividing the sample in 3 groups of esophore, exophore and orthophore subjects. We showed that the magnitude of “trait” fixation disparity was biased by the direction of heterophoria: the more eso the heterophoria, the more eso the average sentence fixation disparity. In sum, despite a large “trait” fixation disparity (in the range of -6.6 to +33.6 min arc), “state” fixation disparities within a sentence were on average -0.9 (\pm 8.7) min arc and, thus, as precise as needed, i.e. within the expected extent of Panum’s area.

Keywords: binocular coordination, fixation disparity, reading, heterophoria, vergence

Introduction

Eye movement research in reading has traditionally been associated with the investigation of visual processing and language comprehension (see, for example: (Kliegl, Nuthmann & Engbert, 2006, Liversedge, White, Findlay & Rayner, 2006b, Rayner, 1998)). Central to the description (and prediction) of eye movement behaviour during reading are saccades and fixations, which are traditionally extracted from the recorded movements of only one eye. But we read with both eyes (binocularly), and besides saccadic eye movements (both eyes move in the same direction) our eyes perform vergence eye movements (the eyes move in opposite directions). In other words, binocular vision of the text requires that the vergence angle between the two visual axes is adjusted for proper fusion of the two retinal images for each fixation. In (theoretically) optimal binocular vision, the principal visual directions of both eyes intersect at the fixation point; slight deviations - fixation disparities (FD) or ver-

gence errors - from this optimal state typically amount to a few minutes of arc and are thus smaller than the Panum’s area (i.e. the range of disparity where sensory fusion of the two retinal images is performed), not leading to double vision. These fixation disparities are called *exo* or *eso* when the visual axes of the eyes converge slightly behind or in front of the fixation point, respectively.

In reading research, ocular alignment was of little relevance to many researchers and a prevalent assumption was that each eye fixates the same character within a word. During the last decade a number of investigations showed that this assumption is not correct, or at least, not in every fixation during reading (Hendriks, 1996, Kirkby, Webster, Blythe & Liversedge, 2008, Nuthmann & Kliegl, 2009, Vernet & Kapoula, 2009): for example, Heller and Radach (1999) reported, that at the end of fixation phases, the eyes were often about 1 to 2 characters apart (character width: 20 min arc). Further, Kliegl, Nuthmann and Engbert (2006) showed that the eyes fixated different letters within a word on 41 % of fixations, while the principal visual directions were more likely to

be crossed in front of the plane of presented text. In contrast to Kliegl et al. (2006), Liversedge, White, Findlay and Rayner (2006b) reported proportions of 53 % aligned, 8% crossed and 39% uncrossed fixations, which reflected a majority of exo fixation disparities (character width: 17.4 min arc). (Note: the classification of fixation disparities as crossed, uncrossed and aligned always reflects a categorization relative to character width.) Up to now, there are no hints for a change of reading parameters (for example, fixation duration) with crossed, uncrossed or aligned fixations across subjects; further, there are no convincing changes in fixation disparity with variations of processing difficulty or linguistic manipulations (Juhasz, Liversedge, White & Rayner, 2007). Thus, the absolute amount or the direction of the fixation disparity as average across a population may be of minor importance for the average reading process.

Moreover, saccadic eye movements during reading are highly predictable, reliable and easy to observe because of their ballistic characteristic; different observers move their eyes in a (mostly) homogeneous pattern through the text (see for an overview, Kirkby et al. (2008) or Rayner (1998)). For vergence, the situation is different: vergence movements are slower, permanently feedback controlled and the shape of the movement is more variable compared to saccadic eye behaviours (Howard, 2002, Howard & Rogers, 2002). Secondly and more important, the static vergence error, i.e. fixation disparity, is different for different observers and might be related to resting states of the vergence system and/ or the coupling of accommodation and vergence (Howard & Rogers, 2002). The reason why an individual's fixation disparity is eso (crossed visual axes relative to the target plane), exo (uncrossed visual axes relative to the target plane), or ortho (aligned visual axes relative to the target plane) is dedicated to other parameters of the binocular system. The phenomenon of fixation disparity was already reported by Hoffmann and Bielschowsky (1900), but the physiological origin and meaning of fixation disparity is still discussed and depends on the model that is assumed to describe vergence behaviour. For example, in feedback control models with integrator elements (Schor, 1979), fixation disparity is the purposeful error signal - the difference between vergence stimulus and vergence response - that drives vergence. Many versions of feedback control theory based models have been investigated; for reviews, see Collewyn and Erkelens (1990), Howard (2002). These models primarily describe dynamic ver-

gence responses; but some authors (Hung & Semmlow, 1980, Schor, 1980) also addressed the stationary case and made predictions for fixation disparity. Further, a neural network model of the disparity vergence system has been proposed by Patel et al. (1997); according to his model, an asymmetry in vergence dynamics (convergence vs. divergence) contributed to individual differences in fixation disparity in non-forced vergence viewing conditions (see, for example: Jaschinski, Svede & Jainta (2008)). More important, Ogle (1954) and Jampolsky et al. (1957) showed (with subjective methods) that a correlation exists between the individual measures of fixation disparity and heterophoria, i.e. the vergence state without a fusion stimulus. A zero heterophoria means that - even without a fusion stimulus - the vergence angle corresponds to the actual viewing distance during testing, as it is the case for zero fixation disparity. This physiological evidence suggests that fixation disparity is a stable characteristic of the individual vergence system.

Why may it be important to know how large a fixation disparity is in particular conditions? It is generally believed that - in order to avoid double vision - the fixation disparity is smaller than Panum's fusional area, i.e. the range of disparity where sensory fusion of the two retinal images is performed. An important notion in this context might be the fact, that the vergence eye movement is feedback controlled by the perception of fusion, which is realized as soon as the eyes were moved disconjugately in a certain amount so that the two images are projected into these Panum's fusional areas. Panum's fusional area is almost always elliptic, that is, it is broader in the horizontal than in the vertical direction (it becomes circular only in special conditions); the width of the ellipsis is dependent on the width and the shape of the target, its contrast, its luminance gradient, its spatial frequency structure and several characteristics more (see for example: Ogle & Prangen (1953); Schor, Heckmann & Tyler (1989); Schor, Wood & Ogawa (1984)). So far it can be summarized, that the width of Panum's area changes with the width of the target, but even for very broad targets it remains smaller than 1 deg as long as the target contains edges of high contrast. So, if one is interested in the processes of fusion during the fixations while reading the width of the fixation disparity gives some information about the maximal tolerated disparity of the fixated words. Typically, there are no reports of double vision during reading, even though the observed fixation disparities are as large as 20 min arc on average and in sin-

gle observations as large as 1 deg; they vary a lot, not even between but also within a subject. We found reports suggesting fusion rather than suppression during fixations while reading (Liversedge, 2008), but, nevertheless, the complete visual information of the words and sentences is available within the image of one eye. Although, there might be a general binocular advantage (Heller & Radach, 1999), fixations may occur where the information from one eye is sufficient, or in other words, where large errors are tolerated and fusion not necessarily achieved.

The interesting question here is how the observed fixation disparities during reading are brought into agreement with the physiological and theoretical descriptions of fusion areas or with the typically described individual aspects of fixation disparity in, for example, optometry research (see above, and, for example, Howard & Rogers (2002)) - which are, as mentioned above, supposed to be small, i.e. amounting up to a few minutes of arc.

In this context, we concentrated the present study on the description of the fixation disparity during fixation phases in reading. Previously reported fixation disparity values always reflected two aspects of fixation disparity and throughout the paper we will call them the “trait” versus “state” aspect of fixation disparity. Generally, a “trait” is defined as a distinguishing feature, which represents long-term and stable aspects of a person. In contrast, “state” aspects represent short-term, variable and situation depending features, which describe only temporary aspects. In this context, the “trait” aspect of fixation disparity represents a general or baseline fixation disparity, which reflects an observer-dependant, typical amount of vergence error (being “exo” or “eso”) (Howard & Rogers, 2002). The “trait” fixation disparity should reflect aspects of the general physiology of the vergence system for each observer; therefore, it should be related to some degree to the individual heterophoria (Ogle, 1954), which we tested for the present data. Moreover, since the “trait” fixation disparity reflects the individual vergence error that is tolerated by the sensory binocular system (in that, diplopia does not occur), the “trait” fixation disparity might be related to these sensory mechanisms. First, we have to consider the size of Panum’s area, i.e. the disparity range within which sensory fusion is possible. We will return to that point later in the context of “state” fixation disparity. Second, the location of Panum’s area in terms of retinal correspondences might have shifted towards the fusion stimulus (see, for exam-

ple: Fogt & Jones (1998a)); this “shift” allows for fusion of stimuli with larger observed motor fixation disparity and it was suggested by the difference between objectively and subjectively measured fixation disparities (Fogt & Jones, 1998b). In other words: the fact that we objectively measure a certain amount of fixation disparity does not imply that the underlying retinal correspondence deviates to the same extent; it just might be shifted (Fogt & Jones, 1998b). Further, we expected this “trait” fixation disparity to be independent of dynamic regulations of vergence, for example, during saccades; remember that the eyes typically diverge for nearly all observers during saccades (see, for example, Vernet & Kapoula (2009)) – independent of the starting level of fixation disparity being “exo” or “eso”. Because of the fact that the sentence was often the only coherent structure in reading tasks, we considered the sentence as basis to extract the “trait” fixation disparity. Thus, the average of all observed average sentence fixation disparities for each observer represents an individual “trait” fixation disparity.

A certain amount of fixation disparity during reading – changes up to a few minutes of arc - is purely due to an imbalance of the movement between the eyes (see, for example, Heller & Radach (1999)) within the sequence of many small saccades and short fixation periods during reading. We will refer to this aspect of fixation disparity as “state” fixation disparity. It represents that part of fixation disparity, which remains after the average fixation disparity of each sentence has been subtracted from each single fixation value.

During saccades the eyes typically diverge and this disconjugacy remains partly at the beginning of the fixation phase and is - more or less completely - reduced by the convergent post-saccadic drift during fixation (Liversedge et al. (2006), Nuthmann & Kliegl (2009) or Vernet & Kapoula (2009)). It has previously been described that incoming saccade amplitudes and serial fixation numbers within the sentence (closely related to fixation position) affect fixation disparities during reading (see, for example, Nuthmann & Kliegl (2009)). Our additional interest was to see if the (isolated) part of “state” fixation disparity was changed only within the (theoretically expected) borders of Panum’s fusional area (Howard & Rogers, 2002) – that is, in a range of one target (character) width. Further, the “state” fixation disparity is supposed to be independent of the “trait” fixation disparity; so even if the reported fixation disparities differ in the amount of crossed (“eso”) or uncrossed (“exo”) fixation

disparities (Liversedge et al., 2006b, Nuthmann & Kliegl, 2009), the analysis of the “state” fixation disparities is unaffected by these differences in the direction of “trait” fixation disparity.

Reading is a rather free condition of eye movements, compared to controlled experimental presentations where stimuli are given at isolated fixed positions; during reading, subjects move their eyes freely through the sentences and all extracted parameters can only be compared afterwards. Usually, in experimental research, repetitions of identical conditions are averaged in order to find stable data. This process is complicated in reading observations. Re-reading is generally supposed to change the eye-movement pattern: for example, fixation durations become shorter and saccade amplitudes larger (Hyönä & Niemi, 1990, Kaakinen & Hyönä, 2007, Raney & Rayner, 1995). Nevertheless, in order to provide a minimal basis of repetitions to be averaged, we presented a set of sentences twice. We checked if fixation disparities were also affected by re-reading.

By doing so, it was the purpose of this study to test if “trait” aspects of fixation disparity correlated with individual heterophoria and whether the “state” fixation disparity produced by dynamic aspects of the eye movements during reading exceeded the borders of one character width.

Methods

Subjects

The 14 subjects had an uncorrected visual acuity of 1.0 or better (in decimal units) in each eye. Subjects ages ranged from 18 to 28 years (mean \pm S.D.: 23 ± 4 years). Myopic, hypermetropic, or astigmatic refractive errors did not exceed 0.5 D (median across subjects: 0.25 D) and no refractive corrections were worn during testing. Each subject gave informed consent before the experiments; the research followed the tenets of the Declaration of Helsinki and was approved by the ethics committee.

Eye movement measurement and calibration

We recorded the movements of both eyes with the video-based EyeLink II. We fixed the head with a chin and forehead rest including a narrow temporal rest in order to minimize artefacts due to possible lateral and oblique head movements. The cameras have been fixed to

the head rest, thus we neither used the helmet to mount the cameras nor the EyeLinkII compensation of head movements. For our purpose, we used only the horizontal raw data - sampled at a rate of 2 ms (500 Hz) - and calibrated each eye separately to transform the screen-coordinates into degrees. The dark pupil system tracks the centre of the pupil by an algorithm similar to a centred calculation with a theoretical noise-limited resolution of 0.01 deg (0.6 min arc) and velocity noise of < 3 deg/s for two-dimensional eye-tracking (details provided by SR Research Ltd, Osgoode ON, Canada). In Jainta, Hoormann & Jaschinski (2009) we showed, that changes in eye position of about 4-6 min arc can be detected using the raw data of the EyeLink II system and using our own monocular calibration. Monocular calibration, i.e. sampling calibration data from the fixating eye only, is important, since fixation disparity is defined as the difference in fixation of a target when viewing changes from monocular to binocular viewing conditions (Fogt & Jones, 1997, Fogt & Jones, 1998a).

During the monocular calibration procedure, subjects were requested to carefully fixate calibration targets that appeared (for 1000 ms) randomly with 100 ms temporal gaps at one of the nine positions within a 3×3 calibration grid. The displacement between the calibration points was 8 deg, so that the calibration grid covered a central space of 16×16 deg; monocular presentations to the right and left eye were randomly interleaved. In order to draw attention to the calibration targets and to facilitate exact fixation, the diameter of the spot initially subtended 1 deg and shrank immediately during 1000 ms to a remaining cross of 8.1×8.1 min arc (stroke width: 2.7 min arc); the remaining cross was visible for 400 ms during which calibration data were stored. Because of the need to calibrate the raw data by physically presented targets, each measured eye position is subject to an uncertainty that can be described by a standard deviation (SD_c) (Fogt & Jones, 1998a, Hoormann, Jainta & Jaschinski, 2008).

Calculation of heterophoria

During calibration, binocular recordings were stored while one eye fixated the target and the fellow eye was not provided with a target. The resulting vergence angle without a fusion stimulus is known as heterophoria (deg). From each calibration, we had 2 average heterophoria measures, one for each eye. Because of the high correlation of both measures ($r = 0.97$), we averaged all heterophoria values, which were available for one person and

thus, described an individual heterophoria as exophore (uncrossed visual axes relative to the target; minus sign), esophore (crossed visual axes relative to the target; plus sign) or orthophore (visual axes intersect nearly perfectly at the visual target).

Procedure, stimuli and apparatus

Subjects had to read 60 sentences from the Potsdam Sentence Corpus (PSC; Kliegl et al. (2006)) silently. Note that we were not interested in cognitive or semantic aspects of reading; we were just interested in acquiring eye movement data collected while typically presented material was read. The PSC provides a broad sentence basis in German, of which we choose sentences of intermediate length. We selected sentences containing 7 to 8 words. The sentence sequence was randomly arranged for each subject. In order to provide a minimal basis of repetitions to be averaged, we presented each sentence twice. We asked the subjects about these repetitions and found the basis of 60 sentences to be large enough, because subjects remarked that they noticed some repetitions of the sentences but were not aware of a complete repetition. Thus, in sum subjects read 120 sentences within the following procedure: after calibration, a fixation cross appeared on the left side of the calibration grid (8 deg left; horizontally at eye level); after 1000 ms a sentence was presented so that the first letter of the first word was positioned at the location of the cross. Sentences were then shown until the subjects clicked on a mouse button to indicate that they finished reading. Then the sentence disappeared and a second fixation cross was presented at the right side of the calibration grid (8 deg right; horizontally at eye level). After 1000 ms this second cross was replaced in 1/3 of the trials by (a) a three-alternative multiple choice question pertaining to the current sentence (the subject answered with a mouse click) or (b) a central fixation cross (midline of the display; horizontally at eye level), which subjects fixated for additional 1000 ms. Thereafter, the left fixation cross appeared again and a new trial started.

We measured eye movements for blocks of 10 sentences; before the first and after the 10th sentence we included a complete calibration phase and combined both regressions to a unique calibration for each block of 10 sentences. After such a block of 10 sentences we included

breaks of a few minutes, so that the subjects could rest and relax their eyes.

For the purpose of monocular presentations during the calibration phases and to control individually the amount of baseline vergence, we used a mirror stereoscope (Howard & Rogers, 2002) with two mirrors at right angle and two VDU screens (CRT Sony F500 T9) at a viewing distance of 60 cm. For each individual inter-pupillary distance (mean \pm SD: 63.5 \pm 3 mm) we adjusted a 6.0 deg absolute baseline vergence, at which we presented the sentences. Note that this way of presenting the sentences is different from prior research; we were mainly interested in vergence changes during reading so that we optimized our setup in order to have an identical demand for all subjects (and always the direction “straight ahead” to the centre of the screens), while as a consequence the stimuli for accommodation and for vergence were slightly different. In other words, the viewing distance was 60 cm considering the stimulus for accommodation, while the stimulus for vergence was slightly (and virtually) in front of or behind the screens at 60 cm (depending on the interocular distance of the subject). But this slight difference between accommodation and vergence stimulus was constant within a subject for all sentence presentations. All stimuli were presented on a white background with a luminance of 33 cd/m² at 100 Hz, while the surrounding room lightning was 43 lux. The letter width was 0.33 deg, i.e. 20 min arc.

Data selection and parameter extraction

Eye movement data were screened for loss of measurement and blinks. Data from sentences without problems were selected by a quality of calibration criterion: we selected only those sentences for which the uncertainty of the measurement due to calibration did not exceed a standard deviation (SD_c) of 20 min of arc, which resembled character width. Trying to describe vergence fixation behaviour and knowing that the character width was outlined as an important marker of vergence accuracy in prior research we took only those measures for analysis which showed a smaller uncertainty due to calibration than a single character width.

Further, we marked saccades within each sentence and selected each saccade with its subsequent fixation period. For saccade detection, we defined saccade onset as the moment in time when the version velocity reached

5 % of the saccadic peak velocity; the saccade offset was defined as the moment in time when the velocity dropped below 10 deg/s (see, for example, (Bucci & Kapoula, 2006, Liversedge et al., 2006b)). Next, we excluded saccades with amplitudes smaller than 10 min arc and with fixation phases shorter than 80 ms or longer than 1200 ms (Liversedge et al., 2006b), so that 7340 fixations remained. Excluding all fixations which were not first fixations in a word (in order to have data comparable to previous reports), left us with 4116 periods of saccade and fixation to be analyzed.

We selected only those sentences, for which we had a complete repetition and for which the fixations in presentation 1 and 2 at the same word were as close together as 1 character width, ensuring that the fixations were - roughly - at the same fixation position considering both repetitions. We used the version signal (i.e. the conjugate movement: $(\text{left eye} + \text{right eye})/2$) to detect the fixation position; the vergence signal, i.e. the difference between both eyes, is independent of this criterion. This last step left us with a very small data set of 388 saccades and fixations, i.e. 194 observations that were available twice.

For each period including saccade and subsequent fixation we calculated or extracted the following parameters: knowing the saccade starting point, we additionally marked the saccade landing position and extracted the saccade amplitude from the version signal. For the complete saccade movement, we extracted the maximum of the vergence error signal (i.e. the disconjugate movement: $\text{left eye} - \text{right eye}$) to describe the trans-saccadic vergence movement. Further, we marked the endpoint of the post-saccadic drift in version and calculated the amplitude of the post-saccadic drift in version and in vergence.

The endpoint of the post-saccadic drift (the minimum in version velocity, first reached after the saccade) was defined as starting point of the fixation phase, for which we calculated the fixation disparity for the first 10 ms of fixation (exo vs. eso; crossed vs. uncrossed). Note, that for all fixation disparity calculations we took the actual fixation position from the version signal and the subjects' pupil distance (ranging from 58 mm to 69 mm between

subjects) to accurately calculate the corresponding geometrically expected vergence angle; then, we subtracted the measured vergence angle from this geometrical angle. We did so, because of the fact that the vergence angle is 6.0 deg, or 360 min arc, for the centrally presented word. However, presenting a sentence on a flat screen implies that the theoretically expected vergence angle for words to the left and the right side of this central gaze position decreases. The deviation of the theoretically expected angle from 6.0 deg, or 360 min arc, is rather small, but amounted up to 4 min arc at the edges of our presentation field. This sounds small but regarding a letter width of 20 min arc, this deviation is as large as 20% of a letter width - for the small proportion of fixations at the beginning or ending of a sentence.

Calculation of "trait" and "state" aspects of fixation disparity

At fixation onset the observed fixation disparities are larger compared to the ones observed at the end of fixation phases (Liversedge et al., 2006b, Nuthmann & Kliegl, 2009). Being interested in the amount of fixation disparities relative to the theoretically supposed width of Panum's fusional area, we selected the largest possible vergence errors; thus, we concentrated on the fixation disparities observed at the very beginning of the fixation phase, even though we knew that these fixation disparities were supposed to be reduced slightly by the "fine-tuning" of the post-saccadic drift in vergence (see above).

Considering the idea of an individual, overall fixation disparity, i.e. the "trait" fixation disparity, we calculated the average fixation disparity for each sentence. Pooling these measures for each observer and extracting the average gave an estimation of the individual "trait" fixation disparity for the observer.

Further, we analyzed each single fixation of each observer by subtracting the corresponding average fixation disparity per sentence. This remaining fixation disparity for each fixation gave the "state" fixation disparities across the sentence fixations, which we then analyzed in respect to incoming saccade amplitude and fixation position.

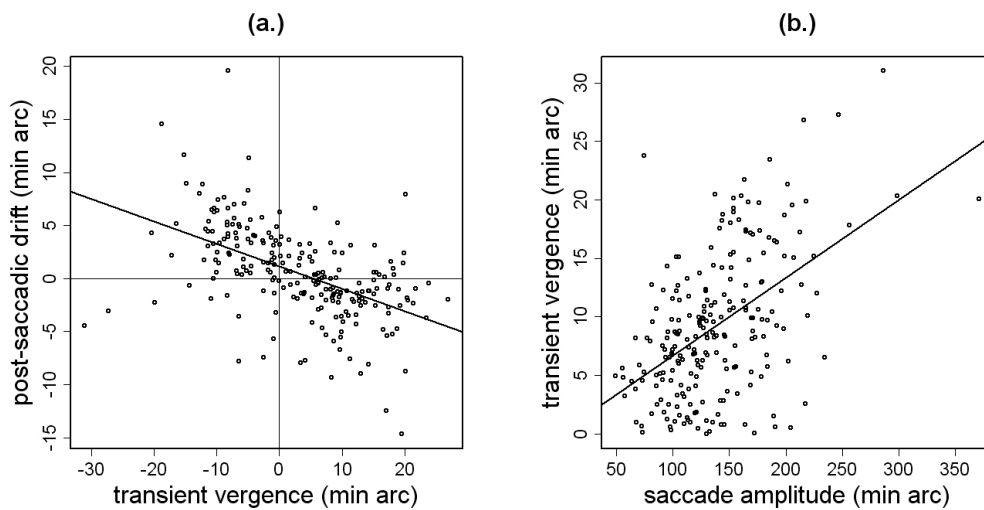


Figure 1: (a) shows the change in post-saccadic drift (min arc) as a function of transient vergence (min arc); in (b) the changes of absolute transient vergence (min arc) as a function of saccade amplitude (min arc) are shown. Lines represent the linear trend within the data.

Results

General eye movement pattern

We observed the following basic version eye movement parameters: for the pooled data set, average (\pm SD) saccade amplitude subtended 137.6 min arc (\pm 47.5), which resembled 6.9 character width, and average fixation duration was 239.2 ms (\pm 68.4). Regarding the vergence movements during the saccade and during the post-saccadic drift, we found the same pattern, that were described in previous research (Hendriks, 1996, Liversedge et al., 2006b, Nuthmann & Kliegl, 2009, Vernet & Kapoula, 2009). During saccades the eyes converged or diverged and this transient vergence error was partly compensated by the following vergence drift during the post-saccadic drift of the eyes ($r = -0.52$; see Figure 1a). Additionally, the amplitude of the transient vergence error correlated weakly with saccade amplitude ($r = 0.50$; see Figure 1b).

Average fixation disparity at the beginning of the fixation phase was 17.9 min arc (\pm 17.2) and resembled one character width on average. The percentage of fixation disparity was 48%, 1% and 51% for crossed, uncrossed, and aligned fixations relative to character width. Thus, our sample reflected mainly eso and aligned fixation disparities (Nuthmann & Kliegl, 2009).

Figure 2 shows the fixation disparity for presentation 1 as a function of presentation 2; as could be seen, very similar version positions in presentation 1 and 2 (see, selection criteria, graph not shown) did produce a wide scatter of fixation disparities. Average fixation disparity was 18.9 min arc (\pm 21.6) for presentation 1 and 17.4 min arc (\pm 20.5) for presentation 2 ($t_{193} = 0.88$; $p = 0.37$).

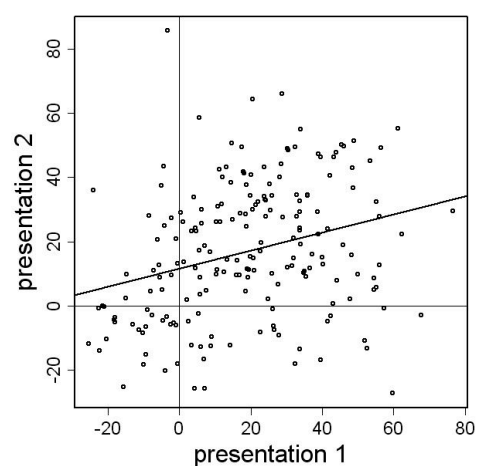


Figure 2: The graph shows the correlation of fixation disparity (min arc) between presentation 1 and 2.

The most important notion is that none of the reported results so far – as shown for fixation disparity - changed from repetition 1 to 2, on average (all t -values < 1).

“Trait” versus “state” fixation disparities

The distribution of the average fixation disparity, calculated for each sentence, had a mean \pm SD of 20.2 ± 18.3 min arc (see Figure 3). The “trait” fixation disparity (based on the average across the sentence fixation disparities for each observer) ranged from -6.6 to 33.6 min arc between observers.

The average “state” fixation disparity within a sentence and across all single fixations amounted to -0.9 min arc (± 8.7) (see the methods section for definitions).

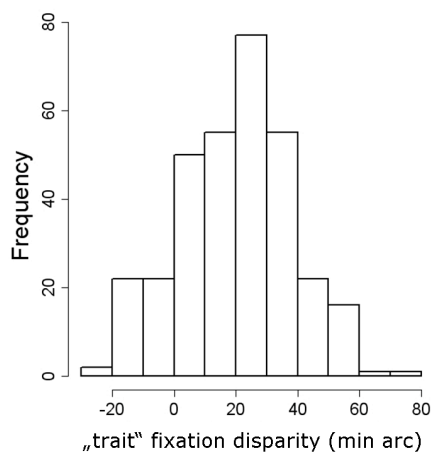


Figure 3: Histogram for the average fixation disparity calculated for each sentence (min arc).

“Trait” fixation disparity and heterophoria

We compared the “trait” fixation disparity with the measurement of heterophoria of each observer (range: 1.9 to -5.8 deg) by dividing the sample in 3 groups: group 1 contained all subjects with a heterophoria more negative than -1 deg (more exo, $N = 3$), in group 2 all subjects with an orthophoria ($N = 6$), i.e. values ranging from -1 to 1 deg, and in group 3 all subjects with a heterophoria more positive than 1 deg (more eso, $N = 5$). Figure 4 gives the relation between “trait” fixation disparity and heterophoria for the three groups. Further, we divided our sample in two groups at the median heterophoria (median = -1.05 deg) and compared the “trait” fixation disparity: the results showed a tendency that the “trait” fixation disparity was smaller (by 11.52 min arc) for the group

having a more exo heterophoria ($t_{10, 0.5} = 1.62$; $p = 0.07$, one-tailed), i.e. a more uncrossed vergence angle between the eyes, when only one eye is fixating.

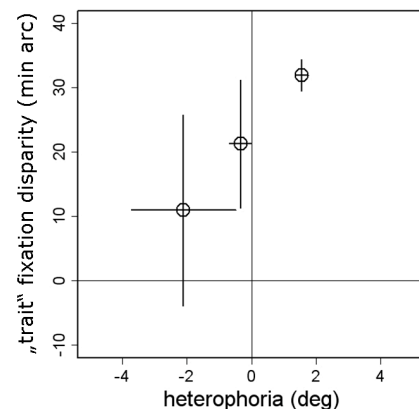


Figure 4: “Trait” fixation disparity (min arc) as a function of heterophoria (deg). The 14 subjects were grouped according to their heterophoria: exophoria (< 1 deg), esophoria (> 1 deg) and orthophoria (in between). The graph shows the average heterophoria measure for each group. The circles mark the averages, while the lines represent standard-deviations.

Additionally, we were interested in the fact if the “trait” fixation disparity is correlated to dynamic aspects of vergence during saccades. For that reason, we correlated the “trait” fixation disparity with the average disconjugacy, i.e. transient vergence, during saccades. Figure 5 shows that there was no relationship between both measures for our 14 observers.

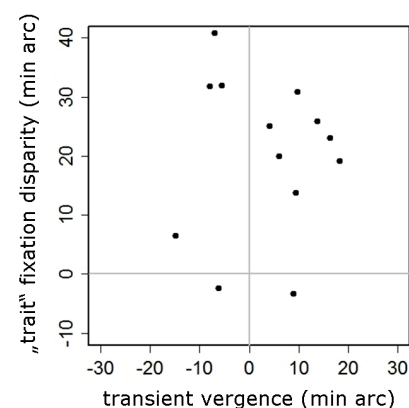


Figure 5: “Trait” fixation disparity (min arc) as a function of average transient vergence during saccades.

“State” fixation disparity and incoming saccade amplitude and fixation position

Because of the fact, that fixation disparity measures were not different for the two presentations, we averaged the “state” fixation disparities across the repetitions to reduce measurement variability. We were interested in the change of the “state” fixation disparity across the sentence and Figure 6 shows that this change in fixation disparity was realized within one character width in 99 % of fixations.

For reading single sentences, the fixation position is not an independent parameter as it would be for, for example, some fixation tasks, where the position of the targets is predetermined by the stimulus conditions. While reading single sentences, the number of the actual fixations, the moment in time after reading onset and the fixation position are closely related. We decided to use fixation position for further analysis – bearing in mind, that it might reflect partly close related reading aspects. Further, knowing the influence of saccade amplitude on vergence errors (Collewijn, Erkelens & Steinman, 1988b, Kirkby et al., 2008, Nuthmann & Kliegl, 2009), we speculated that some variance in the data base might be attributable to saccade amplitude.

We calculated a regression (statistical package R (2008)) including both sources of variance – fixation position and saccade amplitude - to predict “state” fixation disparity. Because of the skewed distribution of the fixation disparity, we transformed the data using square-root transformations; both factors were significant (fixation position (coef (\pm SErr): 0.02 (\pm 0.002); $t_{191, 0.5} = 10.57$, $p < 0.01$) and saccade amplitude (coef (\pm SErr): 0.02 (\pm 0.01); $t_{191, 0.5} = 1.93$, $p = 0.05$)); the overall R^2 of the regression model was 43 %. We ran a second regression analysis for the original fixation disparity measures – that is, before we extracted the “trait” aspect of fixation disparity. Again, both factors were significant (fixation position (coef (\pm SErr): 0.02 (\pm 0.007); $t_{191, 0.5} = 2.82$, $p < 0.01$) and saccade amplitude (coef (\pm SErr): 0.05 (\pm 0.03); $t_{191, 0.5} = 2.11$, $p = 0.06$)); however, the overall R^2 of the regression model was only 8 %.

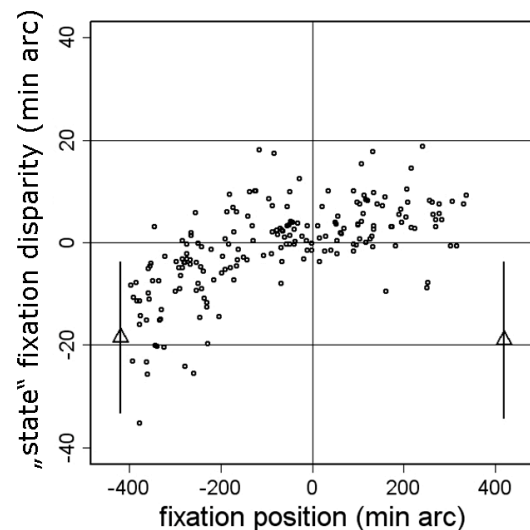


Figure 6: “State” fixation disparity (min arc) as a function of fixation position (min arc) within a sentence. Open triangles show the “state” fixation disparity (\pm SD), which was measured at the starting and end cross, respectively. Additionally, horizontal lines mark the edges of a letter (20 min arc), for the crossed (upper line) and uncrossed (lower line) condition, respectively.

We calculated the “state” fixation disparity (each single observation minus the average fixation disparity for each corresponding sentence) and “trait” fixation disparity (average across all presentations) also for the fixation crosses, which were presented on the left and right side of each sentence, prior to the sentence presentation itself. Figure 6 shows that the “state” fixation disparities for the crosses were shifted into the “exo” direction compared to the reading “state” fixation disparities. The “trait” fixation disparity for the left and right crosses correlated with the individual “trait” fixation disparity during reading (left cross: $r = 0.6$ and right cross: $r = 0.7$, respectively), while the “trait” fixation disparity during reading was significantly more eso than during fixation of the crosses (left cross: $t_{14} = 11.02$, $p < 0.01$ and right cross: $t_{14} = 10.07$, $p < 0.01$, respectively).

Discussion

Reading is a highly skilled task, during which eye movements are made systematically (Blythe, Liversedge, Joseph, White, Findlay & Rayner, 2006, Bucci & Kapoula, 2006, Kirkby et al., 2008, McConkie, Kerr, Reddix & Zola, 1988, McConkie, Kerr, Reddix, Zola & Jacobs, 1989, Rayner, 1998). For our presented study, average fixation durations and saccade amplitudes gave values in the range expected from previous research (see for example, Kirkby et al. (2008)). Most adults' eyes become diverged during saccades (Collewijn, 2001, Collewijn, Erkelens & Steinman, 1988a, Nuthmann & Kliegl, 2009, Vernet & Kapoula, 2009) and this is partially compensated by a post-saccadic convergent drift. Our study showed comparable patterns of results for the vergence change during saccades, but we observed convergence movements also, and the compensation was only partial in many cases, since the convergence (divergence) drift after the saccade was smaller than the remaining divergent (convergent) amplitude which was found at saccade onset. Further, the transient vergence error was related to saccade amplitude, as known before (see for example, Collewijn (2001)).

Showing results comparable to prior research is even more important for our study, because of the fact that we selected a very small sub sample of all observations while subjects read 60 sentences twice. We extracted a small amount of fixations by the criterion that fixations should land within one character widths while reading the same sentence again. To our knowledge, it is a rare procedure to compare binocular coordination across complete repetitions while fixation position is quasi controlled. Generally, re-reading changes the eye-movement pattern: for example, fixation durations become shorter and saccade amplitudes larger (Hyönä & Niemi, 1990, Kaakinen & Hyönä, 2007, Raney & Rayner, 1995). In contrast to this idea we did not find a change in average saccade amplitude, in average fixation duration or in dynamic aspects of vergence (like the disconjugacy during saccade or the post-saccadic drift in vergence) when comparing presentation 1 and 2. Maybe the number of 60 sentences presented in random order for the two readings was large enough so that re-reading effected the eye movements to a less extent. In Raney & Rayner (1995) for example, the short passages were read twice in succession. Further, the lack of re-reading effects in our eye movement data might be due to the criterion of fixation selection (see

above) which reduced - quasi per definition - the difference between both presentations. Additionally and more important for our study, even fixation disparity did not change on average when the sentences were read twice.

In prior research, fixation disparity reported for reading fixations was as large as 1 to 2 characters, and the majority of these fixation disparity seemed to be uncrossed (Heller & Radach, 1999, Liversedge et al., 2006b). Nevertheless, there are also reports of a majority of crossed fixation disparities during reading, but still the deviation of the vergence angle from the theoretically expected one is as large as one letter width in minimum extent, that is, between 17 and 20 min arc (Kliegl et al., 2006). In this context, our data showed several interesting results. On average, the amount of fixation disparity calculated at fixation onset resembled prior findings, i.e. about one character width (Kliegl et al., 2006, Liversedge et al., 2006b). In contrast to Liversedge et al. (2006b) we found the majority of fixation disparities to be crossed (relative to character width), like Kliegl et al. (2006) or Nuthmann & Kliegl (2009) reported.

We started our analysis of fixation disparity values with the assumption that each measurement might reflect two aspects of fixation disparity: One "trait" aspect, which reflects an observer-dependant, typical amount of vergence error (being "exo" or "eso" (Howard & Rogers, 2002)). Another aspect is a temporary, dynamic change during reading, i.e. a "state" aspect of fixation disparity, which is due to the eye movements made to fixate different words. This part of fixation disparity accumulates from one fixation to the next as described by Heller & Radach (1999) or Nuthmann & Kliegl (2009).

Starting with the latter aspect, it has been previously described that incoming saccade amplitudes and fixation numbers (within the sentence; closely related to fixation position) affects fixation disparities during reading (see, for example, Nuthmann & Kliegl (2009)); we confirmed this finding in the present study. Our additional interest was to see if the "state" fixation disparity remained within the (theoretically expected) borders of Panum's fusional area (Howard & Rogers, 2002). As expected from previous research, it was: 99% of all observed "state" fixation disparities were aligned, i.e. smaller than one character width. This fits well to the understanding that a typical width of Panum's fusional area is about 20 to 40 min arc (see for example: Ogle & Prangen (1953); Schor, Heckmann & Tyler (1989); Schor, Wood &

Ogawa (1984)); thus, during the reading process, while the eyes scanned through the text, the “state” fixation disparity changes in the range needed for fusion – that is: the binocular coordination was as precise as needed. Further, the “state” fixation disparity was independent of the “trait” fixation disparity and therefore, the question of a majority of crossed or uncrossed fixation disparities played a minor role when describing the “state” fixation disparity. This kind of differentiating both aspects of fixation disparity might help to understand the general nature of fixation disparity in terms of aspects due to the reading task (“state”) and aspects due to the general and individual baseline fixation disparity (“trait”). At the end, we calculated a regression for the “state” fixation disparities containing fixation position and incoming saccade amplitude; both clarified about 40% of variance. Moreover, the reading “state” fixation disparity changed with fixation position, while the “state” fixation disparity at the left starting cross resembled the one at the right (end) cross (see Figure 5); thus, the fixation position effect seemed to be specific for the reading task in our experiment. Further, because of our reading direction from left to right across the sentence, the fixation position changes mostly parallel the time axis of reading; the further the fixation position is to the right, the longer is the average time on reading or the larger is the number of fixations, on average. These effects could not be disentangled in a task like the one we used in this study. It should be noted that we presented single sentences; when reading includes paragraphs with more than one line the described relation between fixation position, ordinal fixation number and time on reading is only correct for each single line but changes if described across the whole paragraph.

Additionally, saccade amplitude was found to influence “state” fixation disparity: the larger the saccade, the larger the transient vergence error and the larger the remaining, “state” fixation disparity at fixation onset. This relation was weaker than the formulation here might suggest, but it was reflected in the regression analyses we did. Saccade amplitude influenced the magnitude of “state” fixation disparity, which might be a reflection of the difference in the movement of both eyes: the larger the movement the more prominent is the observable difference in the eyes, i.e. the vergence, and the larger is a remaining error across a set of adjacent fixations (Heller & Radach, 1999). Further, our data showed a tendency of smaller and more uncrossed “state” fixation disparity at the starting of the sentences. In sum, the change or vari-

ance in the “state” fixation disparity might purely be due to the dynamic eye position changes during reading and the imbalance of the movement between the eyes, as previously supposed as “moment-to-moment” regulations in vergence (see, for example, Heller & Radach (1999)).

By subtracting the average sentence fixation disparity from each observation, we cleared the resulting “state” fixation disparity from one inherent influence: the individual “trait” fixation disparity for each subject, which reflected the common notion, that people differ in extent and direction of fixation disparity - the first aspect mentioned above (Howard, 2002, Howard & Rogers, 2002). We showed that this “trait” fixation disparity was independent of dynamic regulations during saccades, as was expected. Further, we compared the “trait” fixation disparity with a parameter that we extracted during calibration: the individual heterophoria, which represents the vergence angle that results from tonic vergence and accommodation; this parameter is well-known in optometry and often measured to indicate the individual resting state of the vergence system. As expected from the classical observations of Ogle (1959) and Jampolsky *et al.* (1957) with subjective methods we found a qualitative relationship between “trait” fixation disparity and heterophoria, based on categorized groups of exo, ortho and eso heterophoria (i.e. uncrossed, aligned and crossed conditions). We showed that this heterophoria had an influence on “trait” fixation disparity: the “trait” fixation disparity for subjects having a more distant heterophoria (exophore) was less eso than for subjects having no heterophoria (orthophore). And this continued to esophore subjects: the larger (eso) the heterophoria the larger (eso) was the “trait” fixation disparity. In this context, it showed that the “trait” fixation disparity might be influenced or biased by the individual heterophoria (Howard & Rogers, 2002). Note that this bias did not explain the complete variability in “trait” fixation disparity, but provides a hint of one of its contributors; additional components of “trait” fixation disparity may be related to a reorganisation in retinal correspondences (Fogt & Jones, 1998a), which are discussed in the context of the deviation between subjective and objective measures of fixation disparity, or in an adaptation of the “trait” fixation disparity to the task (or its surrounding parameters), which might clarify the difference in absolute direction of fixation disparities, reported in previous research (Liversedge, Rayner, White, Findlay & McSorley, 2006a, Nuthmann & Kliegl, 2009).

At least, one contribution to the amount of fixation disparity might just be due to fluctuation within the EyeLinkII. The quality of the EyeLinkII for measuring binocular coordination during reading are doubted by some researchers in the field. Drifts and small head changes are supposed to affect the data and - in its extremes - supposed to create the effects. For the reported data we would just like to remark that Figure 6 shows that the changes in fixation disparity occur only during reading the sentence. While the subjects looked at the cross at the left or right side of the presentation, i.e. at the position of the first or last word of the sentence, the EyeLinkII gave exo fixation disparities (as one would expect from previous optometric results for a close viewing distance) and comparable widths for the left and right edge of the presentation field. Thus, a baseline drift during the reading process might not cause the described effects. To quantitatively underline these ideas, further research is needed.

Summarizing our study we would like to outline that - after subtracting sentence average fixation disparity - the remaining fixation disparity, i.e. the "state" fixation disparity, was less than a character width, i.e. clearly within Panum's area of typical width, but still influenced by incoming saccade amplitude and fixation position. Relating the individual average sentence fixation disparity, i.e. the "trait" fixation disparity, to heterophoria showed an important fact: "trait" fixation disparity seems to be biased or influenced by static heterophoria. In other words: despite a large "trait" fixation disparity, which seems to be related to the general error range the vergence system assumes within an observer, the "state" fixation disparity within a sentence is as precise as needed regarding the typical width of Panum's fusional area. Considering classical optometric research this is not at all surprising, but to our understanding it is fruitful to connect reading research results of binocular coordination with standard optometric parameters to enrich the description of vergence eye movements and errors during reading.

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